FINAL REPORT

EAVE-EAST CAVITATION CLEANER FEASIBILITY DEMONSTRATION

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I. EXECUTIVE SUMMARY

The EAVE-East autonomous unmanned untethered submersible test bed has evolved rapidly over the past few years as a very maneuverable vehicle having very precise navigation and control. This system was designed and fabricated by the Marine Systems Engineering Laboratory at the University of New Hampshire.

Concurrently, the technology to clean surfaces of underwater structures by means of a high velocity cavitation jet has also been under development by Daedalean Associates Inc. of Woodbine, Maryland. The source of energy which could be used to generate the high pressure required for such a system was being investigated by the Naval Surface Weapons Center (NSWC). The high pressure gas generator envisioned by NSWC employs the chemical reaction of Lithium metal and water. The purpose of using Lithium is to obtain a very high density energy source which can conceivably be carried by a small underwater robotic vehicle. Water, the oxidizer, can be drawn from the sea, thus, only the Lithium needs to be carried on board.

An experiment was designed to attempt to merge these three technologies to demonstrate the feasibility of utilizing an autonomous submersible to: (1) carry a work package to an underwater structure, (2) serve as a work platform, (3) control the valving and timing necessary for starting the gas generator, (4) clean a section of pipe, and (5) return safely. The specific objectives of the project were as follows:

1. Design mechanical system to accommodate mechanical components of gas generator, nozzle and associated hardware.
2. Determine and compensate for impact of components on hydrodynamics of vehicle.
3. Design and implement method of station keeping for cleaning operation.
4. Design and integrate necessary electronics with vehicle system to control cleaner.
5. Design and implement software necessary to control cleaner and vehicle.
6. Design a series of tests to demonstrate:
    a) The ability of the EAVE-East vehicle to carry this work package to a specific location on a structure.
    b) Station keeping at that location.
    c) Controlling the valving of the gas generator.
    d) Returning safely to the launch boat.

e) In addition to the above vehicle related tests, several static gas generator tests were planned to:
    1) determine the amount of time necessary for pressure buildup.
    2) determine the effective cleaning time.
    3) determine the time necessary for pressures to subside to near zero.

7. Perform tests necessary to demonstrate cleaning of underwater structure by an autonomous robot

The necessary modifications were made to the EAVE-East vehicle to physically accept the cleaning systems (see photos 1 and 2 in Figure 1). A docking mechanism was designed and fabricated in order for EAVE to attach itself to the structure. A nozzle sweeper mechanism was also designed and fabricated in order to clean an area of approximately 6 inches by 6 inches. An electronics package was designed and fabricated to interface between the command computer and (1) the gas generator valves, (2) the docking arms, (3) the nozzle sweeper mechanism, and (4) the fiber optic IR beam pipe sensor. A software work package was written for the command computer, enabling the vehicle to coordinate and control the above during the course of the mission.

Some software gain parameters within the vehicle control algorithm were modified to compensate for the hydrodynamic changes made to the vehicle by the addition of all this equipment.

Tests were conducted to determine EAVE's capability to perform the mission and return safely to the launch boat. These tests were initially conducted without Lithium pellets in the gas generator. After several system corrections, the EAVE-East vehicle successfully navigated to the target member of the structure, docked with the member, undocked and returned to the launch boat.

Tests were then conducted to determine (1) pressure vessel fill time, and (2) reaction time for pressure buildup within the gas generator. Pressure vessel fill time was determined easily. The reaction time for pressure buildup to 8000 psi, however, was unpredictable. Eight tests were conducted. In five of the eight tests, insufficient pressure was generated to rupture the 8000 psi blowout disc. In the three cases where the disc was ruptured, the times were 30 seconds, 9.5 minutes, and 30 minutes. In two of these three tests, the nozzle was found to be clogged and the pipe fixtures had been loosened by the pressure buildup.

On the last few days of testing, the acoustic navigation system became unreliable. The problem appeared to be related to a temperature sensitive component (water temp. was 32 degrees F).

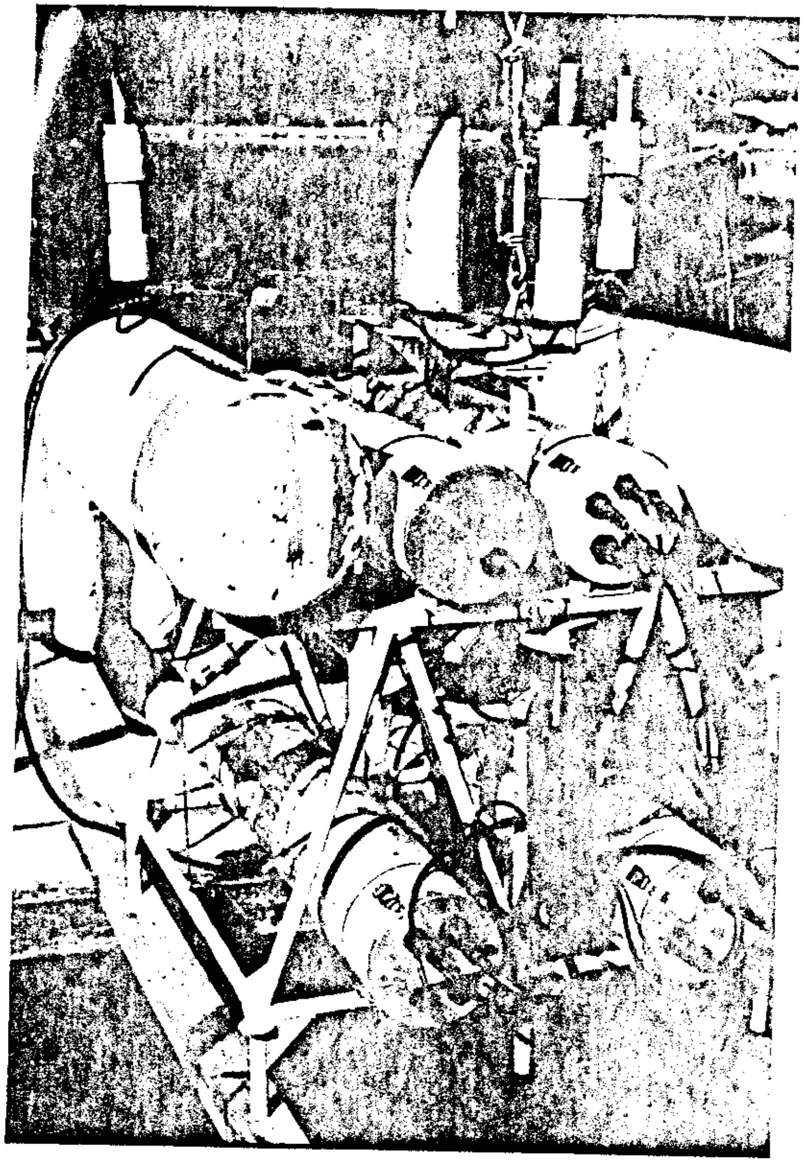


Photo 1
EAVE General Configuration

Photo 2
EAVE/Cavitation Cleaner Configuration

FIGURE 1

The source of this problem has since been found in the acoustic transmitter circuit. Table 1 summarizes the objectives and accomplishments of this project. The results of these tests indicate that the EAVE vehicle's open frame configuration, coupled with its adaptive hydrodynamic configuration algorithm, allowed for very dramatic physical change. The modular design of its software environment made the addition of a work package algorithm very easy to incorporate into the existing software. In other words, EAVE-East has demonstrated its flexibility as a test bed for technology development.

These tests also indicate that further development is needed in developing the gas generator/cavitation erosion nozzle into a system capable of achieving reproduceable results.

II. GAS GENERATOR/CAVITATION EROSION NOZZLE

The cavitation cleaner which consists of the high pressure gas generator and the cavitation erosion nozzle is shown schematically in Figure 2 and operates as follows. First the Lithium pellets/discs were placed in the pressure chamber. The chamber was sealed. A vacuum was then drawn on the vessel to allow for rapid flooding. The vacuum gauge was then removed from the system. Once the vehicle had found the target and securely docked to the vertical member, valves A and B were open to flood the chamber, and closed approximately two minutes later. The pressure would then build up in the vessel until it reached a sufficient value to rupture the blowout disc (8000 psi). The gas and water then pass through the filter and finally emerge through the cavitation erosion nozzle. The nozzle tube and tip assembly are constructed from material that can withstand pressures of 40,000 to 60,000 psi. The cavitation envelope created by the nozzle is shaped like a long cigar and equal work can be produced at any point over its length. This length, or standoff range from a target, is from 1 to 8 inches. Our tests were conducted with a 2 inch standoff distance.

The chemical reaction produced by reacting Lithium metal with water is:

$$2Li + 2H_2O \text{ ------- } 2Li(OH) + H_2$$

The pressure vessel used for this test has an internal volume of 7.26 liters. If 908g of Lithium are used (requiring 1.61 liter volume), the remaining volume for water is 5.65 liters. The reaction would produce approximately 1450 liters of gas at STP. The flow rate would be 7.6 liters/min. at 10,000 psi. The total useful work time would be approximately 45 seconds.

The general shape of the pressure buildup vs. time curve was expected to be of the general shape shown in Figure 3. The exact time to peak pressure and decay time was not known and was to be determined in static tests.

TABLE I

EAVE/CAVITATION CLEANER INTEGRATION
SUMMARY

OBJECTIVES	ACCOMPLISHED	
	YES	NO
INTEGRATE MECHANICAL SYSTEMS	X	
COMPENSATE FOR HYDRODYNAMICS CHANGES	X	
ELECTRICAL INTERFACE/CONTROL	X	
SOFTWARE MODIFICATIONS	X	
CARRY PACKAGE TO TARGET	X	
DOCK WITH STRUCTURE (STATION KEEP)	X	
CONTROL VALVING/SWEEPERS	X	
CLEAN SECTION OF PIPE		X
UNDOCK/RETURN	X	

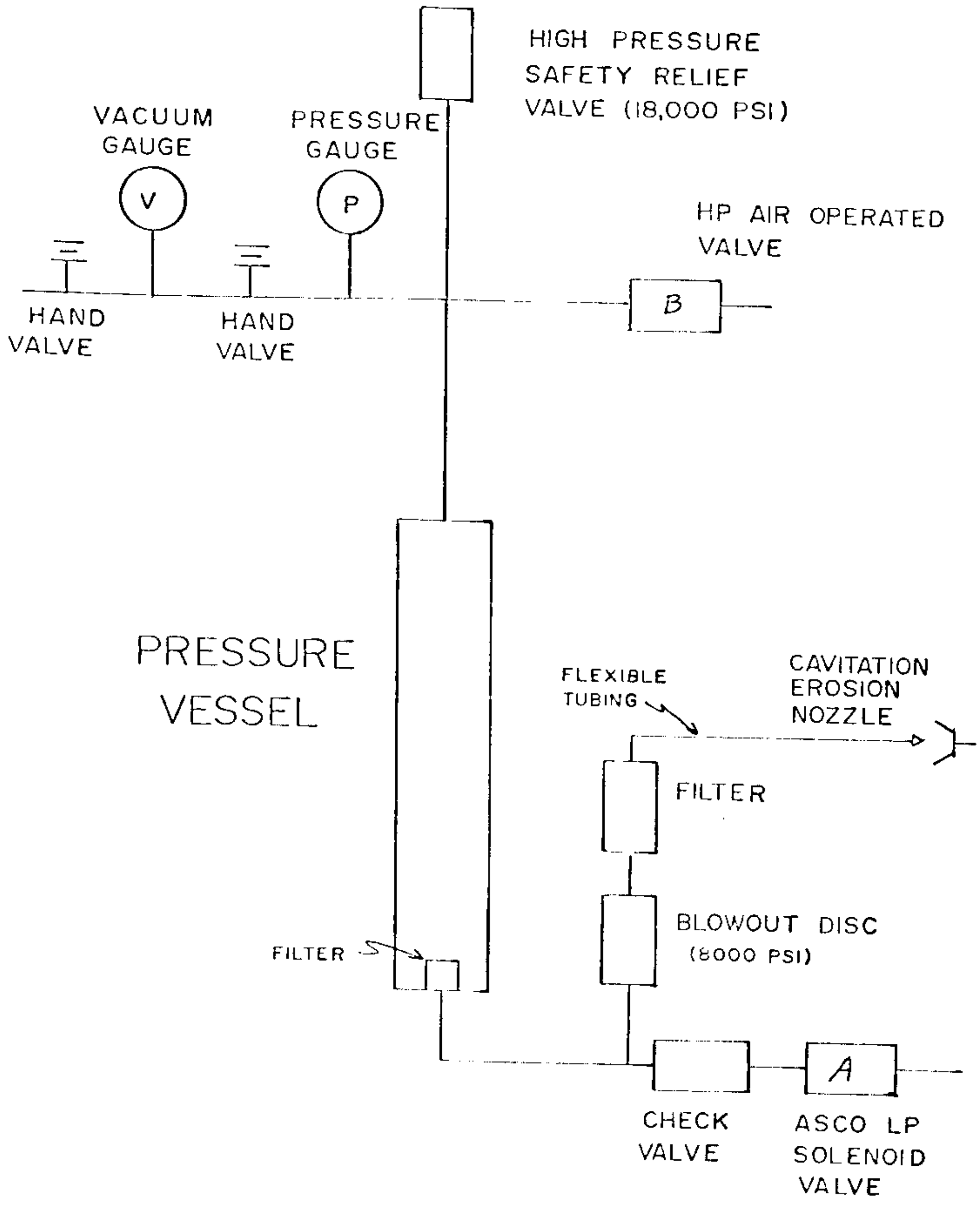


Figure 2: Block Diagram of Cavitation Cleaner System

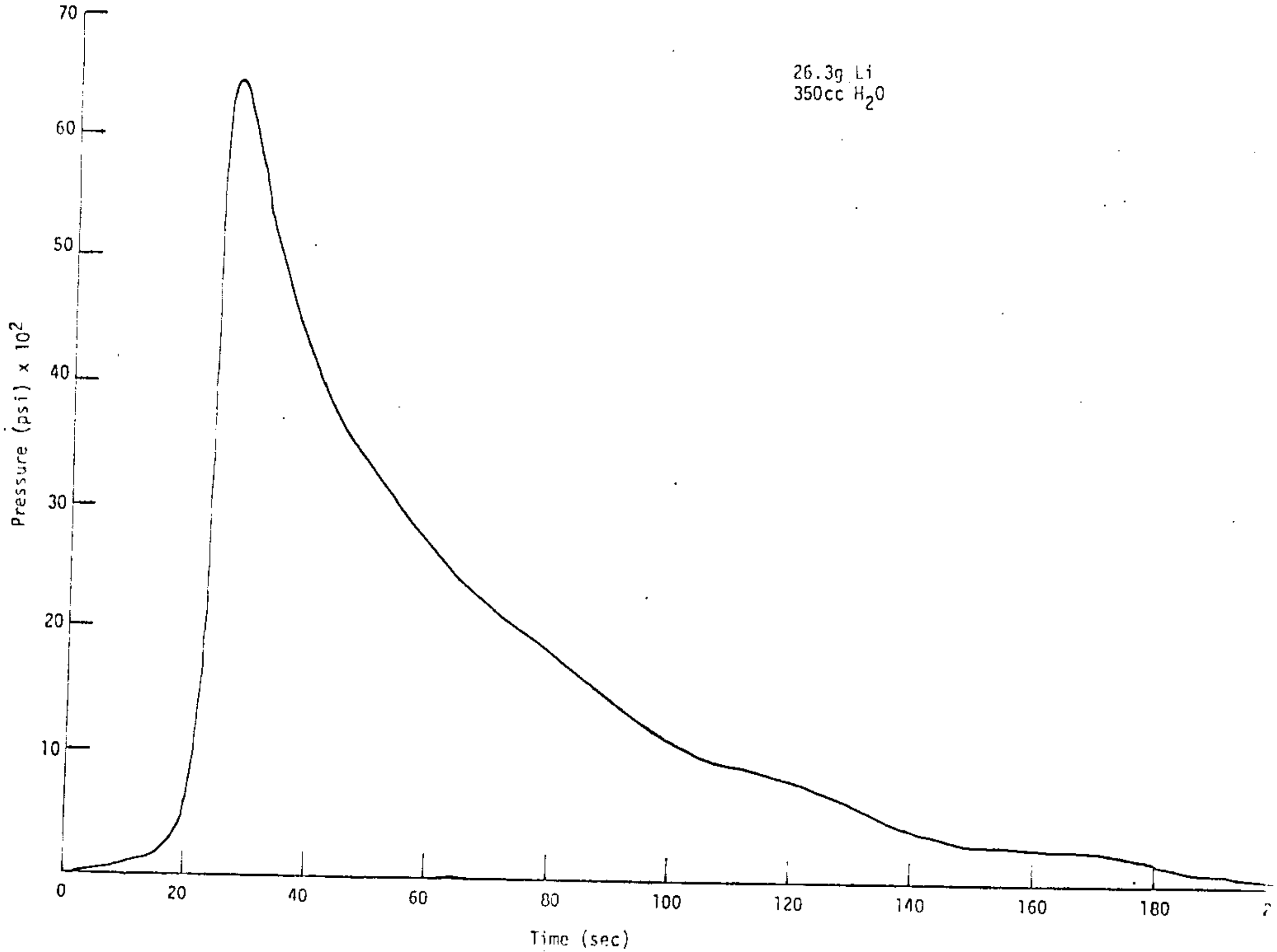


Figure 3: Pressure vs. Time Record

III. MODIFICATION TO THE EAVE VEHICLE

A. Mechanical Modifications

The basic physical EAVE-East configuration is shown in Figure 4. After modifications were made to accept the Lithium gas generator/cavitation erosion nozzle, the physical configuration was that shown in Figure 5. Notice that air operated mechanical grasper arms were added to the vehicle to allow it to dock with vertical structure members.

Mechanically, the problems faced on this project were: (1) adapt the cavitation cleaning system to the EAVE-East vehicle, (2) provide a means of holding the vehicle in position while cleaning, and (3) provide a controlled movement of the cleaning nozzle over a 6 inch X 6 inch target area of pipe.

The physical size and weight of the cavitation cleaning system and the necessity that the pressure vessel remain in a vertical position dictated a major reconfiguration of the EAVE-East vehicle. The pressure vessel, because of its weight (150 lbs.), was mounted at the front of the vehicle, tight against the vehicle frame, keeping it as close to the CG as possible. The vertical thrusters, which were normally mounted there, were moved low on the vehicle's sides. Large buoyancy tanks were added at each side of the pressure vessel to compensate for both weight and moments created there. Battery stacks and computer tubes were shifted several inches to the rear of the frame, to give clearance to the system. Tucked up within the vehicle frame an additional electronics housing was mounted to hold logic and relays for control of the cavitation system valves, clamping system, sweeper controls, and sensor circuitry. The vehicle's normal 50 lb ballast was reduced to 25 lbs and shifted to the rear of the frame to compensate for moments.

To hold the vehicle in place during a cleaning operation a clamping system was devised. The system was composed of upper and lower clamps which closed in lobster claw fashion around the target pipe. The system was driven by air cylinders and controlled by a 5-way solenoid valve. The compressed air required was stored in the two main vehicle bouyancy tubes (100 psi, 5 ft vol). This method could be used as test depths never exceeded 20 feet of water. The clamps could be activated by two means; input from a proximity sensor mounted at the clamps which detected the pipe or through software logic.

In order to clean a 6 inch X 6 inch square area target of the structure it was necessary to sweep the nozzle, which has a jet of about 1/2" diameter. To sweep the nozzle, a carriage frame similar to an x, y, plotter was built, again powered by air pressure. The cylinders were fitted with pneumatic pressure sensors and valving which allows a reciprocating motion in both x and y. With these sensors and valves all that was needed to turn the system on and off was a simple solenoid valve. Speed of movement in x and y could be set separately to give good coverage

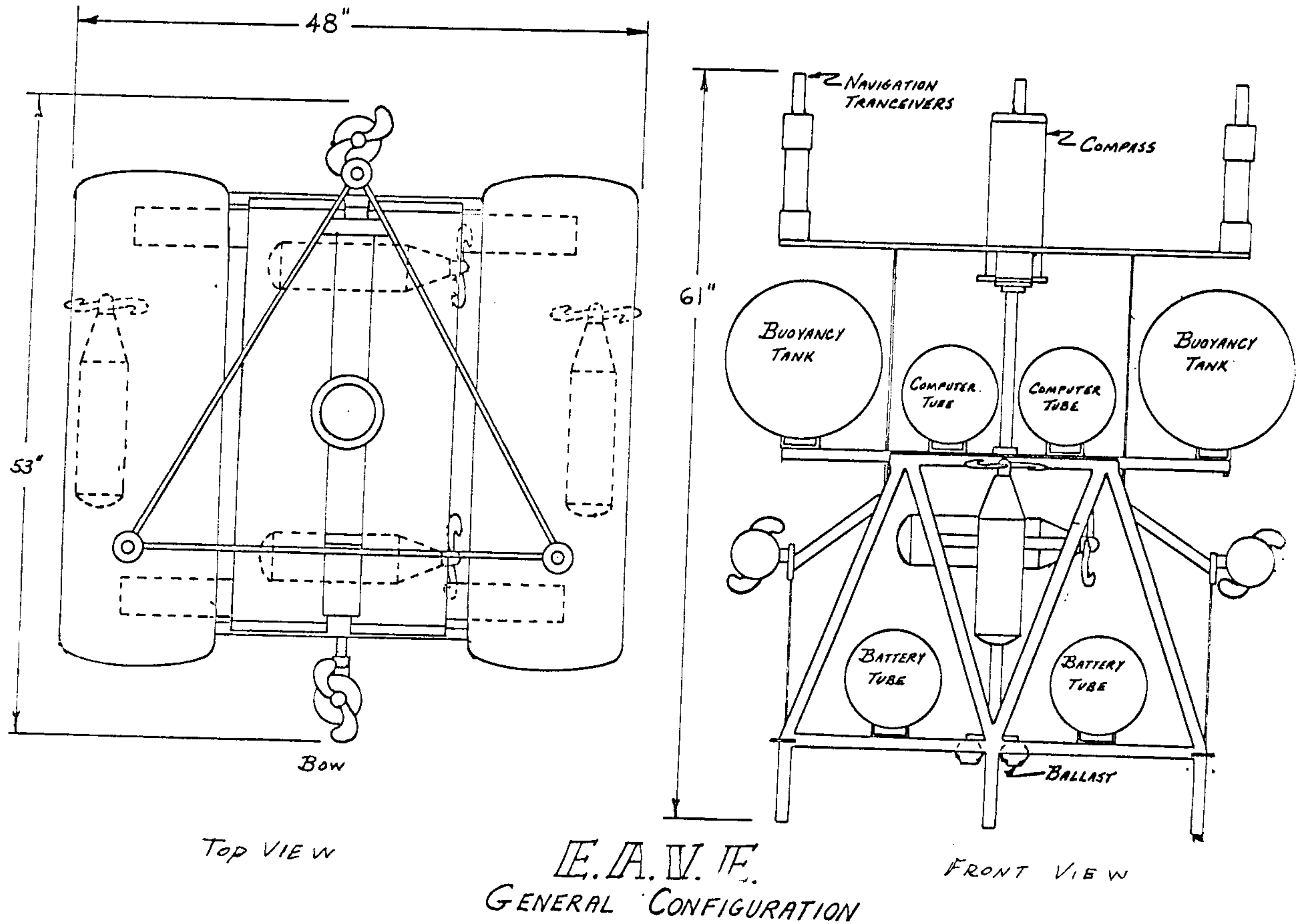
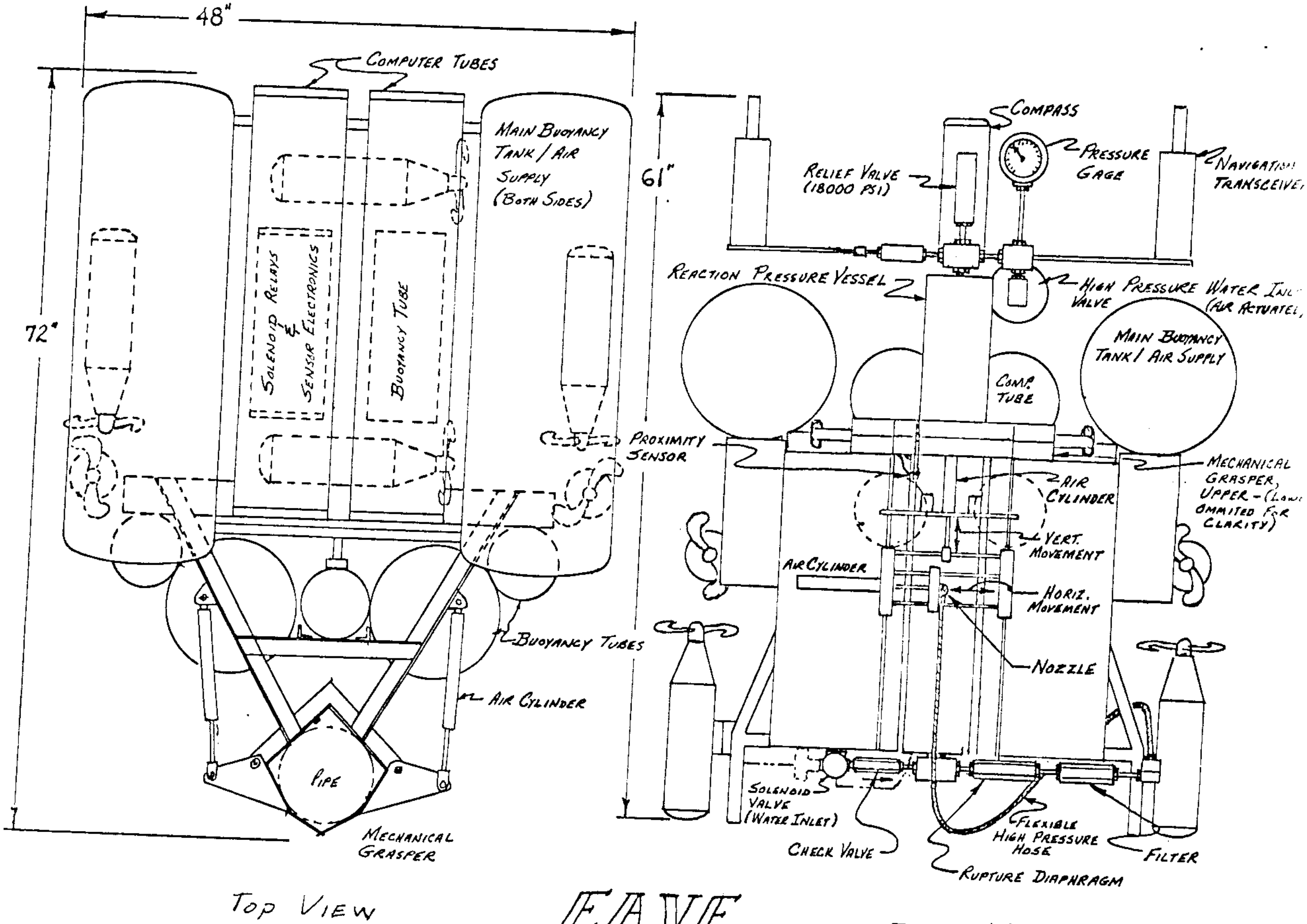


Figure 4: EAVE General Configuration



E.A.V.E.
CAVITATION CLEANING TASK CONFIGURATION

Figure 5

of the target area. The system could run for about three minutes on its available air supply. When tank pressures reached about 50 psi the system would stop (this is inherent to the sensors) assuring that there would always be pressure left for the clamping system.

B. Electronic Modifications

The added functions which had to be controlled due to the addition of the cavitation cleaner were:

1. Opening and closing of the two water inlet valves (top and bottom).
2. Opening and closing of the air activated docking arms (mechanical graspers).
3. Activating and stopping the nozzle sweeper mechanism.
4. Enabling and disabling a fiber optic IR beam pipe sensor.

A schematic of the added electronics to perform these functions is shown in Figure 6. The circuit components were all housed in an electronics bottle which was merely strapped onto the vehicle. This electronics package was connected to the command computer by means of an eight wire cable.

The only modification to the command computer was the addition of eight wires from the bulkhead connector to an existing I/O port on the applications card.

The power necessary to operate the solenoids and valves was provided by the existing battery supply.

C. Software Modifications

The software in the M68000 Command Computer was the only software affected by the addition of the cavitation cleaner to the EAVE-East vehicle.

The software in this computer is written in C language and utilizes a multitasking arrangement of program modules. Figure 7 is a pictorial representation of the various tasks within this computer.

Notice that the addition of this software module (CAV) for the cavitation cleaner work package has little impact on the existing tasks.

This program embodies the intelligence necessary to operate and monitor the cavitation cleaner. It uses messages from the Data Manager Task (DMT) to signal certain events during the course of the mission. The messages received from the DMT indicate the beginning of a path command as well as an event number which the CAV task uses as a trigger to perform a series of instructions.

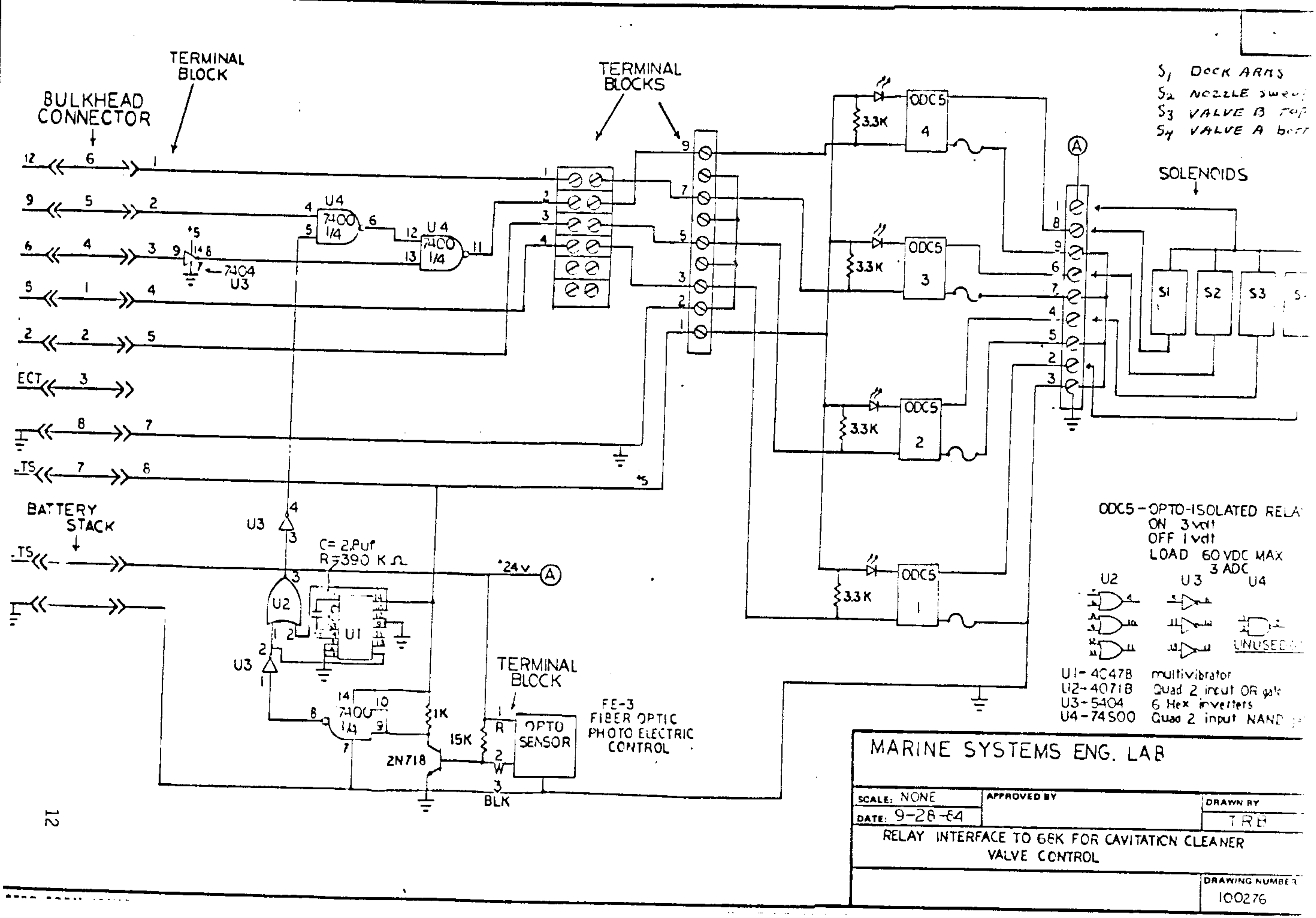


Figure 6: Schematic of Electronic Control for Cavitation Cleaner

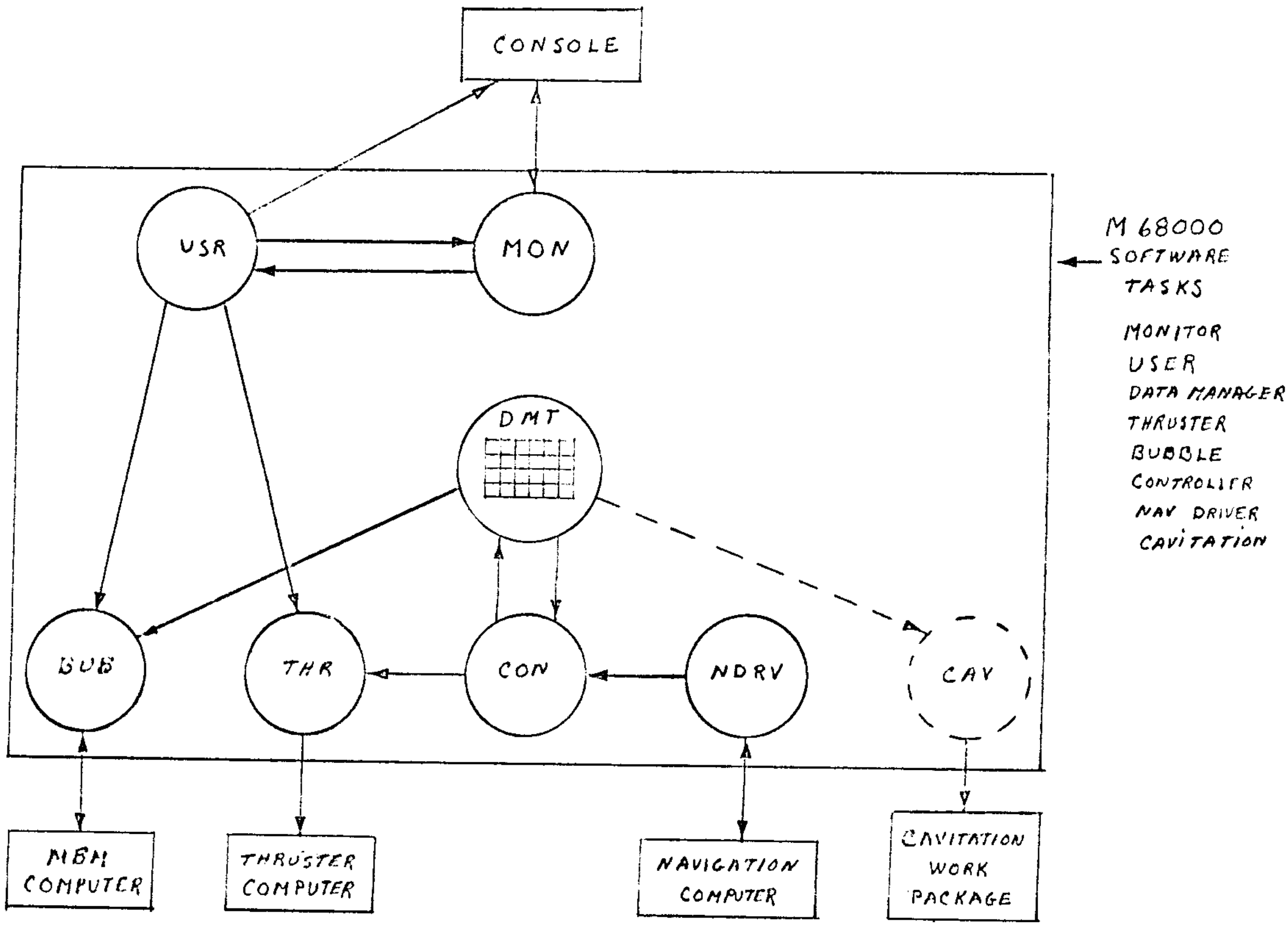


Figure 7: Software Task Arrangement in Command Computer

There are five events, corresponding to five distinct algorithms, residing in the cavitation task. Each event can have up to eight arguments which modify the algorithm's behavior and which are extremely useful in developing, debugging, and diagnosing the vehicle and cavitation cleaner behavior.

IV. DEMONSTRATION TEST MISSION DESCRIPTION

The mission programmed into the vehicle included approaching the structure, sliding sideways along horizontal members and vertically along vertical members as in an inspection mission. The vehicle would then (1) find the target location, (2) dock itself with the vertical target member, (3) test itself for proper docking, (4) operate the cavitation cleaner mechanism, and (5) undock itself and return to the launch barge for recovery.

An underwater structure was constructed primarily of eight inch steel pipes (see Figure 8). A target plate was attached to one of the vertical support members of the structure. This target could be removed by divers after a cleaning operation and replaced.

V. TEST RESULTS

A. Gas Generator/Cavitation Erosion Nozzle

Preliminary tests were conducted on the cavitation cleaner system to verify reliable safe operation and to determine two timing parameters. The two parameters were (1) time required to flood the pressure vessel, and (2) time required to build up pressure sufficient to rupture the 8000 psi blowout disc. These two parameters were to be entered into the software cavitation task arguments to control (1) flood valve timing, and (2) the time at which the nozzle sweeper would be turned on.

NSWC personnel were on hand to conduct all tests of the cavitation cleaner system.

The flooding tests were straight forward. It was determined that the pressure vessel would flood in 1.25 minutes if both top and bottom valves were open, and 1.5 minutes if just the bottom valve was opened.

Determining the pressure buildup time, however, proved to be far more complicated for several reasons. The system did not reliably build up sufficient pressure to break the blowout disc. Of the eight tests conducted, the pressure reached its critical value only three times (see Figures 9 and 10). The pressure buildup times for these three events were 30 seconds, 9.5 minutes, and 34 minutes.

In two of the three tests which reached critical pressure, the nozzle was found to be clogged and pipe fixtures had been loosened by the high pressures. In one case the flexible line (15,000psi) to the nozzle was ruptured. Only in one test did the

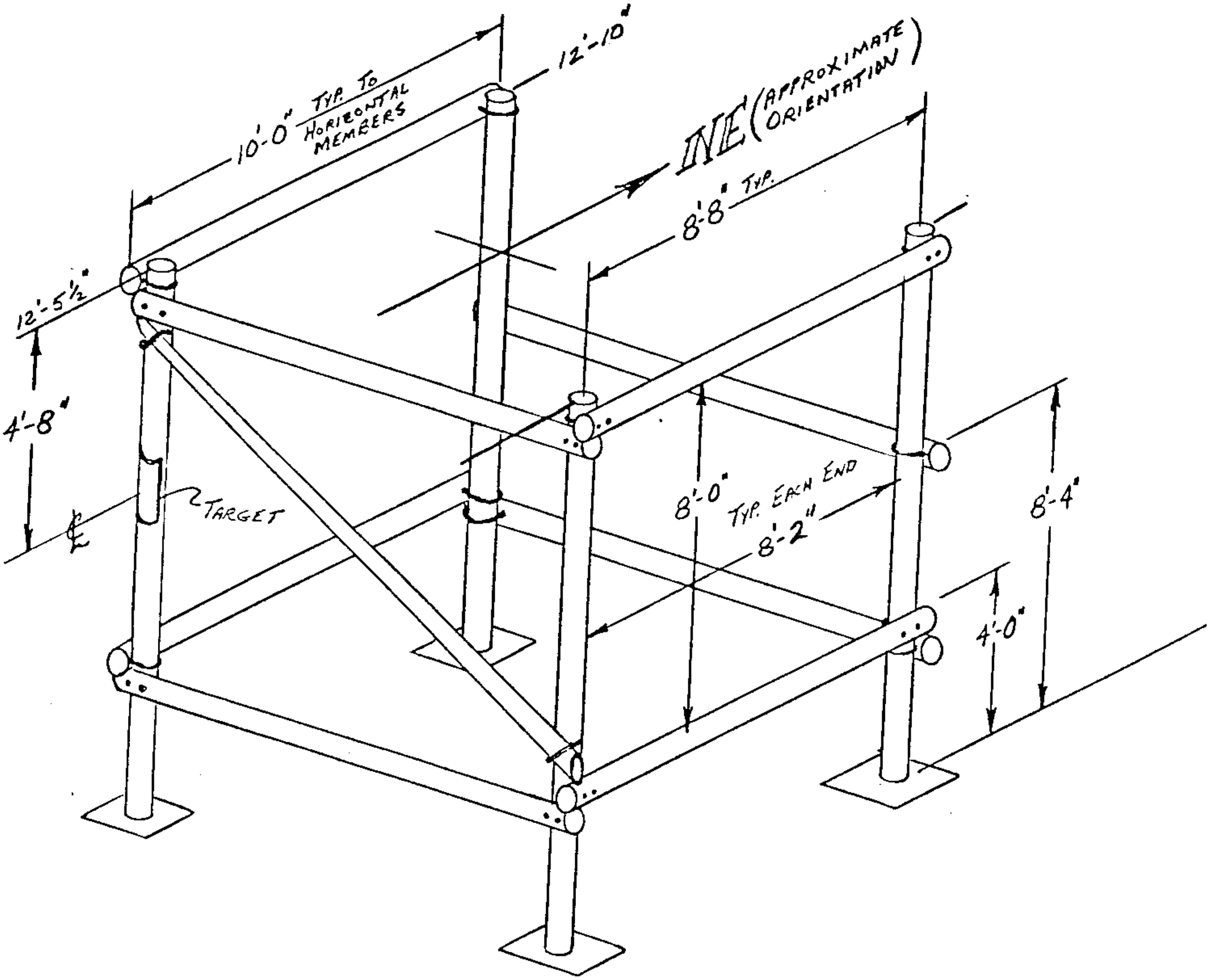


Figure 8: Steel Underwater Structure

Test #	Amount Lithium	Flood Time Minutes	Total Pressure Buildup Time Minutes	Rupture 8000 psi Blowout	Nozzle Condition	Comments
1	1/4# pellet w/grease	3	20	No	--	Failed
2	1/4# pellet w/grease	2	20	No	--	Failed
3	1/4# pellet & 9 discs w/grease total approx. .5#	2	34	Yes	O.K.	--
4	Three 1/4# pellets w/grease total = .75#	2	60	No	--	Failed
5	Two 1/4# pellets & 20 discs w/grease total = 1#	2	50	No	--	Failed
6	Two 1/4# pellets & 15 discs no grease total = .85#	.5	.5	Yes	clogged	Broke 15000 psi hose & loosened fittings
7	1/4# pellet & 12 discs w/grease total = .65#	1.5	52	No	--	Failed
8	1/4# pellet & 13 discs light grease total = .7#	2.5	9.5	Yes	clogged	Broke pressure gauge loosened fittings

Figure 9: Tabulation of Cavitation Cleaner Tests

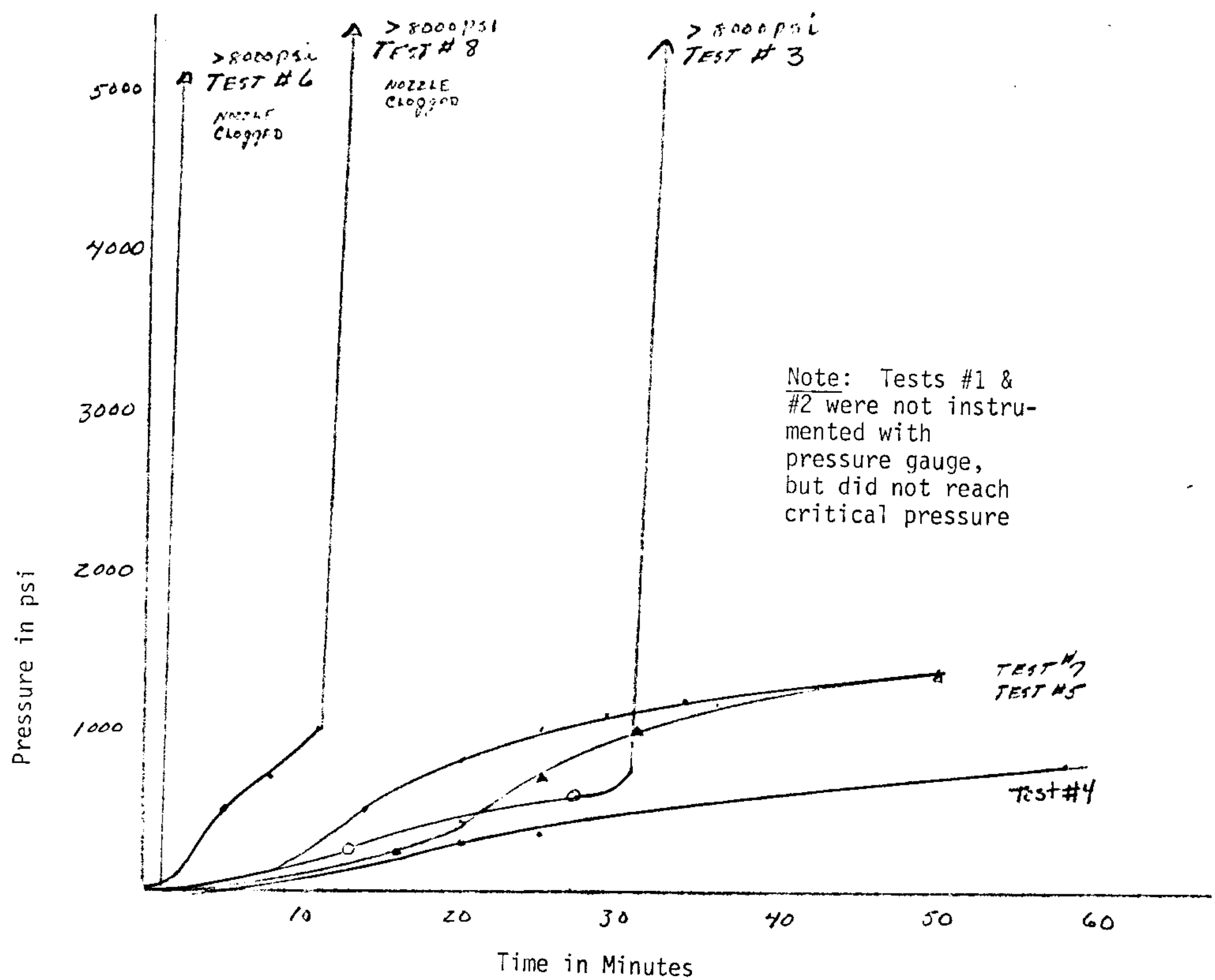


Figure 10: Pressure Buildup Curves of Cavitation Cleaner Tests

system appear to operate properly and expel the water and gases out the nozzle. No evidence of cleaning could be found on the target. This leads one to suspect insufficient pressure at the nozzle due to pressure leaks or losses in the filters.

It also appears that the filter system was not working properly since the nozzle clogged in two of the three critical pressure tests.

It appears that one of the critical determinants of pressure build up time is the amount of grease coating applied to the Lithium.

The reaction of the Lithium with water must be delayed. The fill time of the pressure vessel was approximately 75-90 seconds. If the chemical reaction begins sooner, pressure from the generated gas prevents complete filling of the chamber. The Lithium was coated with grease to provide this delay. It was found, however, that in most cases sufficiently high pressure (8000 psi) was not reached in a reasonable amount of time.

When no grease coating was used, the Lithium started to react immediately and prevented proper filling of the vessel, a large amount of LiOH precipitated from solution and clogged the filters, line, and nozzle.

A near solution to the delay and reaction rate problem was achieved by tying the Lithium to the top of the chamber with solder and flooding from the botttom only. The Lithium was only lightly coated with grease. The reaction could not in this case begin until the chamber was nearly filled. The reaction heat melted the solder and allowed the Lithium to drop into the water. A reasonable (9.5 minutes) delay time was achieved in this test.

A major technical problem is filtration. It appeared that the dissolved LiOH would precipitate out of solution at the filter, in the lines, and in the nozzle. This problem requires serious effort in order to allow the nozzle to work properly.

The piping used on the cavitation cleaner had many joints. Problems in maintaining the seal of these joints occurred at peak pressures in the range of 10,000 psi to 18,000 psi. The pressure rating of the fittings was 20,000 psi. Failure of these joints can be attributed to either shock loading during pressure build up or insufficient torque/pre-load at tightening.

B. EAVE-East Vehicle Performance

1. Hydrodynamic Control

Prior to conducting the entire mission, the hydrodynamic changes to the vehicle created by the addition of the cavitation cleaner and docking mechanism had to be determined. Once determined, the software controller gain values had to be modified to correct for the changes. This was easily accomplished in the field by the operator.

The vertical separation between the center of gravity and the center of bouyancy was reduced from 8 inches to 6 inches by the hardware additions. This, however, still provided for sufficient pitch and roll stability. Vehicle performance in this aspect did not appear to be degraded.

There was a noticeable change in vehicle maneuverability, as one might expect. The most severely affected was the heading control (rotational control). Substantially different gain values were input to this portion of the controller. Only modest changes had to be made to the horizontal control and vertical control loop gains. Once these gains were adjusted the vehicle control accuracy was +1 ft. in x and y (horizontal), +0.5 ft. in z (vertical), and +12 degrees in 0 (heading). This is not as precise as the vehicle was without the hardware changes, however, it was deemed precise enough to perform this test.

2. Mechanical System Modifications

The air operated system which controlled both the docking arms and nozzle sweeper was susceptible to moisture in the lines which would freeze overnight (these tests were conducted in New Hampshire in November/December). This was corrected by simply placing the vehicle in the water for 5 to 10 minutes prior to conducting the tests.

The docking arms and sweeper mechnanisms worked properly after a few hardware problems were corrected.

3. Electronic/Software System Modifications

The electronic interface to the system worked well in the lab, but when assembled on the vehicle behaved erratically. The problem was traced to the mechanical assembly within the electronics bottle. Contact was being made from a metal frame to a relay connection. Once this was corrected, the interface functioned properly.

The cavitation task software also performed well. Its designed-in flexibility allowed the operator to vary several crucial parameters in the field based on observed performance. This feature saved a great deal of field testing time.

4. Navigation System

One major problem arose during the last week of testing (December). The acoustic navigation system began to fail. It was receiving only one transponder return (long baseline system) and hence could not compute a position. It was determined that a circuit element in either the transmitter/receiver or the transponders was being affected by the cold temperatures (32 degrees F water).

Since that time, the problem has been traced to a capacitor in the transmitter circuit. This element has since been replaced with a temperature insensitive capacitor.

5. Overall Vehicle Performance

During the course of testing, several problems arose as discussed earlier. After correction, the vehicle did several times perform the inspection, docking, work package control, undocking and return to the support boat successfully.

VI. CONCLUSIONS

1. An autonomous submersible cavitation cleaning system was created through the combination of three separate technologies: a cavitation nozzle, a Lithium high pressure gas generator, and a delivery and control vehicle.

2. The cavitation cleaning system did not function properly. These tests, however, served to define the basic problem areas. These problems include: (1) reaction delay control, (2) reaction rate, and (3) filtration and various other system flaws.

3. The EAVE-East vehicle does appear to be capable of (1) carrying a work package (cavitation cleaner) to an underwater structure, (2) docking, (3) controlling the work package, (4) undocking, and (5) returning safely.

4. Very dramatic physical changes can be made to the vehicle and their hydrodynamic effects corrected easily by adjustments to the software controller gain values.

5. The electronic and software changes to the vehicle were implemented with little impact on the basic system. These changes were treated as modular additions.

VII. RECOMMENDATIONS

A. Gas Generator/Cavitation Erosion Nozzle

If the existing concept is to operate as a system, much engineering work will have to be accomplished. Specific areas which require correction are:

(1) Reaction Rate Control. A better method of retarding the reaction should be devised. Coating pellets manually with grease will probably not produce repeatable results. A method of retaining the Lithium away from the water during pressure vessel flooding must be devised, otherwise the reaction begins prematurely and presents further flooding of the chamber.

(2) Filtration. The existing filter system is not adequate. Much Lithium Hydroxide was found beyond the filters and in the nozzle. It would appear that a major filter redesign is necessary and/or a means of preventing the precipitate (LiOH) from coming out of solution must be found.

(3) Pipe Fittings. Several times the pipe fittings became loose during tests. First, the number of fittings should be reduced and second, a torque wrench should be used to tighten all fittings to a prescribed amount of force.

(4) Nozzle. This nozzle has a very small work area of approximately .5 inches squared. A better system would be to have a fan shaped work beam. This would allow a much larger work area coverage in the limited time provided by the gas generator.

B. EAVE Vehicle System:

(1) Heading Control. The heading (yaw) control algorithm should be modified by the addition of an integral term. This would better stabilize the yaw oscillation of the vehicle.

(2) Compass Heading. In the vicinity of the steel structure (i.e. within it) the magnetic compass is useless. A method should be devised to automatically switch between acoustic heading input and magnetic compass input during the course of the mission.